

Embedded System Design for Wearable Health Monitoring

Riya Kulkarni¹, Manav Srivastav²

Associate Professor, Students

Department of Embedded Systems

Greenfield College of Engineering

riyakulkarn4ii@gmail.com, manavsrivastav_8@yahoo.com

Abstract

Wearable health monitoring devices are becoming very popular in recent years due to growth in embedded systems, low power electronics, wireless communication and smart sensors. These devices continuously track physiological parameters such as heart rate, body temperature, blood oxygen level, motion activity and many other health indicators. Embedded system design plays a very important role in making these wearable devices reliable, small in size, low power and comfortable for long time usage. This paper presents a detailed review of embedded system architecture, hardware components, software design, communication methods and power optimization techniques used in wearable health monitoring systems. Challenges like battery limitation, data accuracy, sensor calibration and security issues are also discussed. The paper also highlights recent trends such as AI integration, edge processing and IoT connectivity in wearable devices.

Keywords: *Wearable devices, Embedded systems, Health monitoring, Sensors, Low power design, IoT, Edge computing*

1. Introduction

Healthcare monitoring is shifting from hospitals to personal continuous monitoring using wearable devices. Fitness bands, smart watches, ECG patches and smart shirts are some examples. These devices help in real time monitoring and early detection of diseases. Embedded systems are the core part of these devices because they integrate sensors, microcontrollers, memory, communication units and power management in a compact form.

Wearable health monitoring systems are designed to be light weight, portable and energy efficient. Unlike traditional medical devices, they operate on small batteries and need to function for many days without charging. Therefore, efficient embedded design is necessary. The main objective of this paper is to explain how embedded systems are designed for wearable health monitoring and what are the important considerations in hardware and software design.

2. Architecture of Wearable Health Monitoring System

The architecture of a wearable health monitoring system is designed in such a way that it can continuously sense physiological signals, process them in real time, and transmit useful information to external devices like smartphones or cloud servers. Since these devices are small, battery-operated and worn on the human body, the architecture must be compact, energy efficient, and reliable.

A typical wearable device is built using five major building blocks: **sensors, embedded processor, memory, communication module, and power management unit**. All these components work together in a coordinated manner.

2.1 Sensors Layer

This is the first layer of the system where physiological data is captured from the human body. Different sensors are used depending on the health parameter to be monitored.

- PPG sensor for heart rate and SpO₂
- ECG electrodes for cardiac activity
- Temperature sensor for body temperature
- Accelerometer and gyroscope for motion and fall detection
- GSR sensor for stress analysis

The signals obtained from the body are very weak and noisy, therefore they cannot be directly given to the processor.

2.2 Signal Conditioning Unit

Before reaching the processor, sensor signals pass through analog circuits that perform:

- Amplification of weak signals
- Noise removal using filters
- Conversion of analog signals to digital form using ADC

This block ensures that accurate and clean data is fed into the embedded processor.

2.3 Embedded Processor (Microcontroller Unit)

The microcontroller is the brain of the wearable device. It controls all operations such as:

- Reading data from sensors
- Running signal processing algorithms
- Managing communication
- Controlling power states
- Storing temporary data in memory

Low power MCUs like ARM Cortex-M, MSP430, or ESP32 are generally used because they support multiple ADC channels, sleep modes and integrated communication interfaces.

2.4 Memory Unit

Memory is required to store:

- Temporary sensor readings
- Processed health data
- Firmware and program code
- Logs before transmission

Both RAM and Flash memory are used. Some advanced devices also use external EEPROM for extended storage.

2.5 Communication Module

This block allows the wearable device to communicate with smartphones or cloud servers.

Common communication technologies:

- Bluetooth Low Energy (BLE) – most preferred
- Wi-Fi – for high data rate devices
- NFC – for short range pairing
- Zigbee – in some medical applications

The communication module sends processed data to mobile apps where user can see reports.

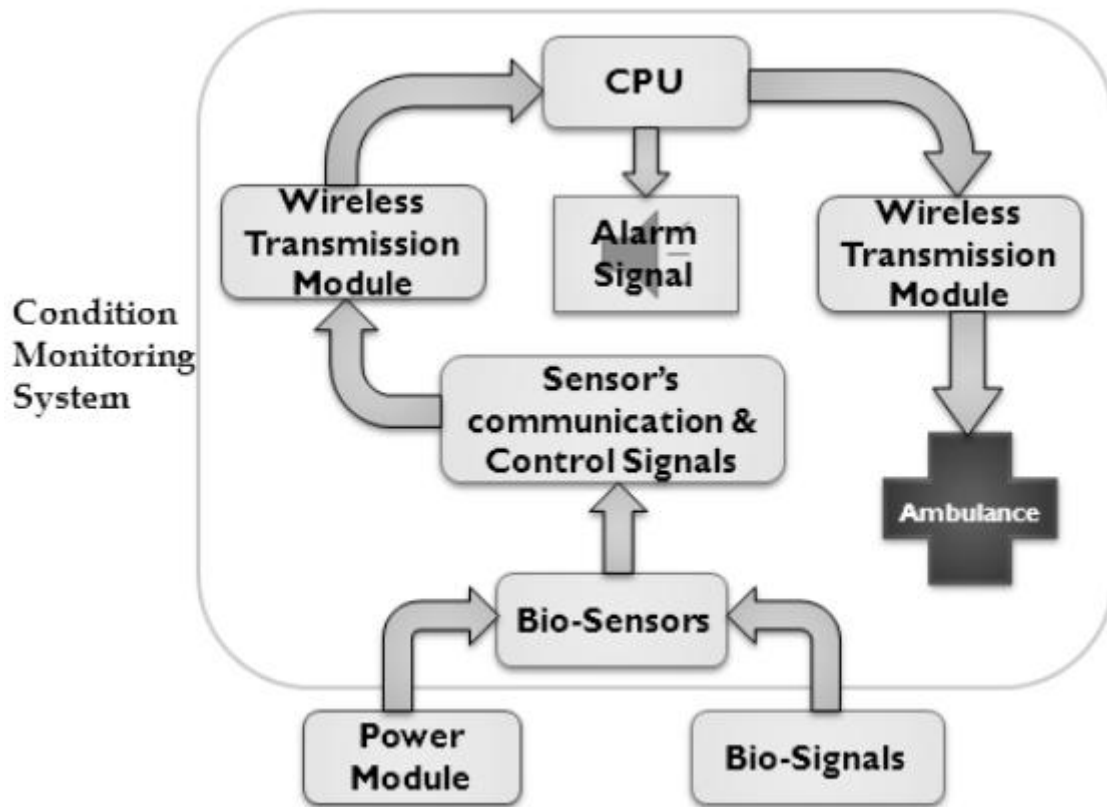


Figure 1: Basic architecture of wearable health monitoring system

3. Hardware Components

3.1 Sensors (Elaborated)

Sensors are the most critical hardware elements in a wearable health monitoring system. They are responsible for capturing physiological and motion-related signals directly from the human body. The accuracy, size, power consumption, and placement of sensors greatly affect the overall performance of the wearable device. Since wearables are continuously in contact with the body, sensors must also be comfortable, safe for skin contact, and capable of working under motion and sweat conditions.

In wearable devices, sensors generally convert physical or biological signals into electrical signals that can be processed by the embedded microcontroller.

A. Photoplethysmography (PPG) Sensor

PPG sensors are widely used in smartwatches and fitness bands to measure **heart rate** and **blood oxygen saturation (SpO₂)**.

- Works by emitting light into the skin and measuring the reflected light.

- Variations in reflected light correspond to blood volume changes.
- Uses LEDs (green, red, infrared) and a photodiode.

Design Considerations:

- Proper skin contact is necessary.
- Sensitive to motion artifacts.
- Requires optical isolation from ambient light.

B. Electrocardiogram (ECG) Sensor

ECG sensors measure the electrical activity of the heart.

- Uses electrodes placed on the skin.
- Provides more accurate cardiac monitoring compared to PPG.
- Used in medical patches and chest straps.

Design Considerations:

- Requires good electrode-skin contact.
- Needs high gain amplification and noise filtering.
- More power consumption than PPG.

C. Temperature Sensor

Temperature sensors measure body temperature for fever detection and metabolic monitoring.

- Common types: Thermistors, digital temperature ICs.
- Placed in contact with skin.

Design Considerations:

- Must compensate for external temperature.
- Requires calibration for skin vs core body temperature difference.

D. Accelerometer and Gyroscope

These are motion sensors used for:

- Step counting
- Activity recognition
- Fall detection
- Sleep pattern monitoring

Accelerometer measures linear motion, while gyroscope measures angular motion.

Design Considerations:

- Low power operation
- High sensitivity to detect small movements
- Proper placement to reduce noise from random motion

E. Galvanic Skin Response (GSR) Sensor

GSR sensors measure electrical conductance of skin, which changes due to sweat gland activity.

- Used for stress and emotional state monitoring.

Design Considerations:

- Requires stable skin contact
- Sensitive to humidity and sweat

F. Blood Pressure Sensors (Cuffless)

Modern research focuses on cuffless BP monitoring using PPG and ECG combination.

- Uses Pulse Transit Time (PTT) method.
- Still under development for commercial accuracy.

Table 1: Sensors are the most important part. Common sensors used are:

Sensor Type	Parameter Measured	Example Application
PPG Sensor	Heart rate, SpO ₂	Smart watches
Temperature Sensor	Body temperature	Fever monitoring
Accelerometer	Motion, steps	Activity tracking
ECG Sensor	Cardiac activity	ECG patches
GSR Sensor	Skin response	Stress detection

These sensors must be small, accurate and low power.

3.2 Microcontroller / Processor

The microcontroller (MCU) or processor is the central unit of a wearable health monitoring device. It acts as the brain that controls sensors, processes data, manages communication and handles power optimization. Since wearables operate on very small batteries, the choice of MCU is very critical.

Commonly used low-power microcontrollers include **ARM Cortex-M series (M0/M3/M4/M33)**, **MSP430**, **nRF52 series**, and **ESP32** (when Wi-Fi is required).

Key Requirements of MCU in Wearables

• **Low Energy Consumption**

The MCU should consume very little current in active as well as sleep modes. Many MCUs provide ultra-low power modes consuming only a few microamps.

• **ADC Channels for Sensor Input**

Wearable sensors give analog signals. MCU must have multiple high-resolution ADC channels (10- to 16-bit) to accurately convert these signals into digital form.

• **Sleep and Deep Sleep Modes**

MCU should support multiple sleep states. It wakes up only when sensor sampling or communication is required.

• **Small Footprint**

Since wearable devices are compact, MCU packages like QFN, BGA or chip-scale packages are preferred.

• **Integrated Communication Support**

Built-in interfaces like I²C, SPI, UART, BLE, and sometimes Wi-Fi reduce the need for external chips and save space and power.

Role of MCU in Wearables

- Periodic sampling of sensor data
- Running filtering and signal processing algorithms
- Managing BLE/Wi-Fi communication
- Storing temporary data in memory
- Controlling power to sensors and modules

3.3 Signal Conditioning Circuit

Signals obtained from physiological sensors are usually very weak (in millivolts) and noisy due to body movement, muscle activity and external interference. These signals cannot be directly processed by the MCU. Therefore, signal conditioning circuits are required between sensors and MCU.

Main Components of Signal Conditioning

•Amplifiers

Operational amplifiers (Op-Amps) are used to increase the amplitude of weak ECG, PPG or GSR signals.

•Filters

Filters remove unwanted noise:

- Low-pass filters remove high frequency noise
- High-pass filters remove baseline drift
- Notch filters remove power line interference (50/60 Hz)

•Analog to Digital Converter (ADC)

After conditioning, analog signals are converted into digital form using ADC. Some designs use MCU's internal ADC, while high precision devices use external ADC ICs.

Importance in Wearables

Proper signal conditioning improves accuracy of health readings and reduces errors due to motion artifacts.

3.4 Wireless Communication Module

Wireless communication allows the wearable device to send health data to smartphones, tablets or cloud servers for visualization and analysis.

Bluetooth Low Energy (BLE)

BLE is the most preferred technology because:

- Very low power consumption
- Suitable for short range communication
- Supported by all smartphones
- Secure pairing and encryption features

Other Communication Options

Technology	Use Case	Advantage	Limitation
Wi-Fi	High data rate devices	Long range	High power use
Zigbee	Medical networks	Mesh support	Less common in phones
NFC	Device pairing	Very low power	Very short range

The communication module is often integrated with MCU (like nRF52, ESP32) to reduce hardware size.

3.5 Power Source

Power management is one of the biggest design challenges in wearables. Devices are expected to run for several days on a small battery.

Rechargeable Batteries

- **Li-ion and Li-Po batteries** are commonly used
- Lightweight and high energy density
- Rechargeable using USB or wireless charging

Power Management Circuit

Includes:

- Voltage regulators
- Battery charging IC
- Protection circuits
- Fuel gauge for battery level monitoring

Energy Harvesting Techniques

Some advanced wearables use:

- **Thermoelectric generators** (body heat)
- **Piezoelectric generators** (body motion)
- **Solar cells** (light energy)

Though energy harvesting cannot fully power device, it helps in extending battery life.

4. Software Design in Wearables

Software is responsible for sensor reading, data processing, communication and power management.

4.1 Real Time Operating System (RTOS)

RTOS ensures tasks like sensor sampling, data processing and communication happens within time limits.

4.2 Data Acquisition and Filtering

Noise from body movement affects signals. Digital filters such as low pass, moving average filters are used.

4.3 Communication Protocol Stack

BLE stack, TCP/IP stack (for Wi-Fi), and custom protocols are implemented.

4.4 Firmware Updates

Over-the-air (OTA) updates are important to improve functionality without replacing device.

5. Power Optimization Techniques

Power is the biggest challenge.

- Duty cycling of sensors
- Deep sleep modes of MCU
- Efficient BLE transmission intervals
- Turning off unused peripherals

Technique	Description	Benefit
Duty Cycling	Sensor active only when needed	Saves battery
Sleep Mode	MCU in low power state	Extends life
Data Compression	Send less data	Less transmission power

6. Data Processing and Edge Computing

Instead of sending raw data to cloud, some processing is done inside device.

- Heart rate calculation from PPG
- Step counting from accelerometer
- Arrhythmia detection using simple algorithms

This reduces data transmission and power use.

7. Security and Privacy Issues

Health data is very sensitive.

- Data encryption using AES
- Secure pairing in BLE
- Authentication before data access

If security is weak, personal health data can be misused.

8. Challenges in Wearable Embedded Design

1. Limited battery size
2. Accuracy of sensors during movement
3. Heat dissipation in small size

4. Wireless interference
5. Comfort and ergonomics

Designers must balance performance and comfort.

9. Applications of Wearable Health Monitoring

- Continuous heart monitoring for cardiac patients
- Fitness and activity tracking
- Elderly fall detection
- Sleep monitoring
- Stress and mental health tracking

10. Emerging Trends

- AI based anomaly detection inside device
- Flexible electronics and smart fabrics
- Integration with IoT healthcare platforms
- Energy harvesting techniques
- Miniaturized biomedical sensors

11. Case Study: Smart Wrist Band

A smart wrist band typically includes:

- PPG sensor for heart rate
- Accelerometer for motion
- Cortex-M4 MCU
- BLE module
- 200 mAh battery

It can operate for 5–7 days with optimized firmware.

12. Future Scope

Future wearable devices will be more accurate, smaller and intelligent. Integration of AI and machine learning will allow early disease prediction. Flexible circuits will make devices more comfortable to wear.

13. Conclusion

Embedded system design is the backbone of wearable health monitoring devices. Careful selection of sensors, microcontrollers, communication modules and power management techniques is required to build reliable wearable devices. With advancements in embedded technology and IoT, wearable health monitoring systems will play a major role in preventive healthcare. Though many challenges exist like power limitation and security issues, continuous research is improving these systems. Wearable technology will become an important part of everyday life in healthcare monitoring.

References

1. J. Y. Khan, "Wearable Sensors for Health Monitoring," IEEE Sensors Journal, 2019.
2. S. Patel et al., "A review of wearable sensors and systems," Journal of NeuroEngineering, 2018.
3. A. Pantelopoulos, "Wearable sensor-based systems for health monitoring," IEEE Trans. Systems, 2017.
4. R. Paradiso, "Wearable health care system," Annual Review of Biomedical Engineering, 2019.
5. H. Ghasemzadeh, "Energy efficient wearable systems," IEEE Embedded Systems Letters, 2020.
6. M. Chen, "IoT based healthcare monitoring," IEEE Communications Magazine, 2018.
7. P. Bonato, "Advances in wearable technology," IEEE Engineering in Medicine, 2017.
8. T. Tamura, "Wearable Photoplethysmographic Sensors," Sensors, 2020.
9. L. Clifton, "Signal processing in wearable devices," Physiological Measurement, 2019.
10. K. Yang, "Security issues in wearable health devices," IEEE Access, 2021.